

How FACTS Controllers Benefit AC Transmission Systems

1# POOJA JOSHI ,A.P IN ELECTRICAL AND ELECTCRONICES DEPARTMENT,

C.U SHAH COLLEGE OF ENGG. AND TECHNOLOGY, WADHVAN, SURENDRNAGAR

2#HIRVANIYA SIDHARTH V. M.E 09EIAPS604, INSTITUTE OF ENGG. AND TECHNOLOGY, ALWAR

Abstract--This paper provides a summary of one of the three planned presentations on the topic of “FACTS Fundamentals. This paper is on Part I of the session and focuses on a summary of the issues and benefits of applying FACTS controllers to AC power systems. The overall process for system studies and analysis associated with FACTS installation projects and the need for FACTS controller models is also discussed. Finally, an introduction to the basic circuits of several FACTS controllers is provided with a focus on their system performance characteristics. This paper is designed to be accompanied by the presentation material.

I. INTRODUCTION

With the ongoing expansion and growth of the electric utility industry, including deregulation in many countries, numerous changes are continuously being introduced to a once predictable business. Although electricity is a highly engineered product, it is increasingly being considered and handled as a commodity. Thus, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. In the evolving utility environment, financial and market forces are, and will continue to, demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. To achieve both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the *existing* transmission system infrastructure is required. Improved utilization of the existing power system is provided through the application of advanced control technologies. Power electronics based equipment, or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today.

FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines. Traditional solutions to upgrading the electrical transmission system infrastructure have been primarily in the form of new transmission lines, substations, and associated equipment. However, as experiences have proven over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and *controversial*. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line

construction. The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and T& communities. With respect to FACTS equipment, voltage sourced converter (VSC) technology, which utilizes self-commutated thyristors/transistors such as GTOs, GCTs, IGCTs, and IGBTs, has been successfully applied in a number of installations world-wide for Static Synchronous Compensators (STATCOM), Unified Power Flow Controllers (UPFC), Convertible Series Compensators (CSC), back-to-back dc ties (VSC-BTB) and VSC transmission. In addition to these referenced and other applications, there are several recently completed STATCOMs in the U.S., in the states of Vermont, California, and Texa. In addition, there are newly planned STATCOMs in Connecticut and Texas, as well as a small STATCOM (D-VAR) planned for BC Hydro and several other locations. Other installations of power electronic equipment includes Distributed Superconducting Magnetic Energy Storage units (D-SMES). These aforementioned transmission system installations are in addition to the earlier generation of power electronics systems that utilize line-commutated thyristor technology for Static Var Compensators (SVC) and Thyristor Controlled Series Compensators (TCSC).

II. CONTROL OF POWER SYSTEMS

A. Generation, Transmission, Distribution

When discussing the creation, movement, and utilization of electrical power, it can be separated into three areas, which traditionally determined the way in which electric utility companies had been organized. These are illustrated in Figure 1 and are:

- Generation
- Transmission
- Distribution

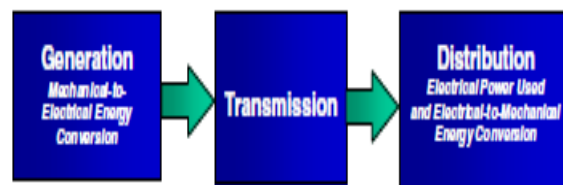


Figure 1. Illustration of the creation, movement, and utilization of electrical power

Although power electronic based equipment is prevalent in each of these three areas, such as with static excitation systems for generators and Custom Power equipment in distribution systems, the focus of this paper and accompanying presentation is on transmission, that is, *moving* the power from where it is generated to where it is utilized.

B. Power System Constraints

As noted in the introduction, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. The limitations of the transmission system can take many forms and may involve power transfer between areas (referred to here as transmission bottlenecks) or within a

single area or region (referred to here as a regional constraint) and may include one or more of the following characteristics:

- Steady-State Power Transfer Limit
- Voltage Stability Limit
- Dynamic Voltage Limit
- Transient Stability Limit
- Power System Oscillation Damping Limit
- Inadvertent Loop Flow Limit
- Thermal Limit
- Short-Circuit Current Limit
- Others

Each transmission bottleneck or regional constraint may have one or more of these system-level problems. The key to solving these problems in the most cost-effective and coordinated manner is by thorough systems engineering analysis, as described later in this paper.

C. Controllability of Power Systems

To illustrate that the power system only has certain variables that can be impacted by control, consider the basic and well-known power-angle curve, shown in Figure 2. Although this is a steady-state curve and the implementation of FACTS is primarily for dynamic issues, this illustration demonstrates the point that there are primarily three main variables that can be directly controlled in the power system to impact its performance. These are:

- Voltage
- Angle
- Impedance

One could also make the point that direct control of power is a fourth variable of controllability in power systems.

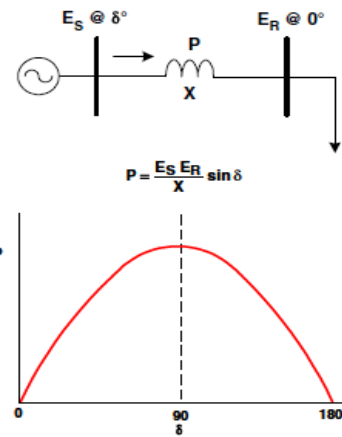


Figure 2. Illustration of controllability of power systems

With the establishment of “what” variables can be controlled in a power system, the next question is “how” these variables can be controlled. The answer is presented in two parts: namely conventional equipment and FACTS controllers.

Examples of Conventional Equipment For Enhancing Power System Control

- Series Capacitor
- Controls impedance
- Switched Shunt-Capacitor and Reactor
- Controls voltage
- Transformer LTC
- Controls voltage
- Phase Shifting Transformer
- Controls angle
- Synchronous Condenser
- Controls voltage
- Special Stability Controls
- Typically focuses on voltage control but can often include direct control of power
- Others (When Thermal Limits are Involved)
 - Can included reconductoring, raising conductors,
 - dynamic line monitoring, adding new lines, etc.

Example of FACTS Controllers for Enhancing Power

- **System Control**
- Static Synchronous Compensator (STATCOM)
- Controls voltage
- Static Var Compensator (SVC)
- Controls voltage
- Unified Power Flow Controller (UPFC)
- Convertible Series Compensator (CSC)
- Inter-phase Power Flow Controller (IPFC)
- Static Synchronous Series Controller (SSSC)
- Thyristor Controlled Series Compensator (TCSC)
- Controls impedance
- Thyristor Controlled Phase Shifting Transformer (TCPST)
- Controls angle Super Conducting Magnetic Energy Storage (SMES)
- Controls voltage and power

As mentioned earlier, the key to solving transmission system problems in the most cost-effective and coordinated manner is by thorough systems analysis. This includes comparing the system benefits available by conventional equipment and from FACTS controllers. There is an important distinction to make when considering the differences in these two solution options. Figure 3 is an illustration of a few cycles of voltage at power system frequency. This figure shows that the speed of mechanical switches (primarily circuit breakers) for conventional equipment solutions can be as fast as a couple of cycles of 60 (or 50) Hz. This *speed* of switching in and of itself may be fast enough to solve many power system constraints. Although there is a vast improvement in switching time from mechanical to power electronic based solutions (Figure 3 illustrates that the speed of power electronics switches is a fraction of a cycle), the main benefit that FACTS controller solutions provide is the “cycling/repeatability” and “smooth control” that accompanies the power electronic based switching. In other words, a mechanically switched based (conventional) solution is usually a “one and done” or “on or off” impact to the power system in the time frame needed for power system stability, whereas the power electronic based solution can provide a smooth, continuous, and/or repeatable option for power system control. Thus by applying power electronic based solutions to alleviate power system constraints, it is not just “speed” but “cycling” and “smooth control” that is gained.

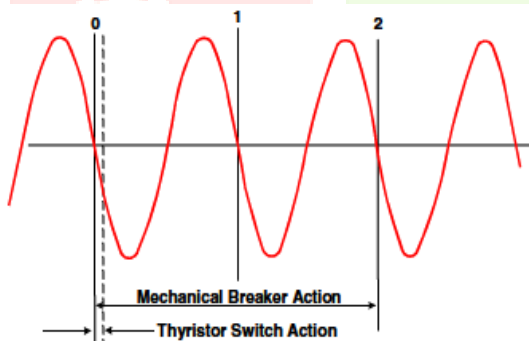


Figure 3. Illustration of the speed of power system control

D. Benefits of Control of Power Systems

Once power system constraints are identified and through system studies viable solutions options are identified, the benefits of the added power system control must be determined. The following offers a list of such benefits:

Increased loading and More Effective Use of Transmission Corridors Added Power Flow Control

Improved Power System Stability Increased System Security Increased System Reliability Added Flexibility in Siting New Generation Elimination or Deferral of the Need for New Transmission Lines.

The advantages in this list are important to achieve in the overall planning and operation of power systems. However, for justifying the costs of implementing added power system control and for comparing conventional

solutions to FACTS controllers, more specific metrics of the benefits to the power

system are often required. Such benefits can usually be tied back to an area or region for a specific season and year at a defined dispatch (usually given by an ISO or equivalent) while meeting the following criteria, for example:

- Voltage Stability Criteria
 - e.g., P-V voltage or power criteria with minimum margins
 - e.g., Q-V reactive power criteria with minimum margins
- Dynamic Voltage Criteria
 - e.g., avoiding voltage collapse
- -e.g., Minimum transient voltage dip/sag criteria (magnitude and duration)
- Transient Stability Criteria
- Power System Oscillation Damping
 - e.g., Minimum damping ratio
- Others Each of the above-listed items can usually be measured in terms of a physical quantity such as power transfer through a critical transmission interface, power plant output, and/or area or region load level.

This allows for a direct quantification of the benefits of adding power system control and provides a means to compare such benefits by the various solution options considered, whether they be conventional or FACTS based.

III. PHASES OF POWER SYSTEM STUDIES FOR FACTS INSTALLATION PROJECTS

- Figure 4 shows the author’s view of the overall process for system studies associated with FACTS installation projects. The presentation that accompanies this paper goes into details of the various phases of power system studies and what items must be focused on for each phase including the modeling requirements. The presentation will start with initial feasibility studies to determine system constraints and reinforcement Losses
- Interaction with other devices
- Evaluate Economics of Each Option’s Costs vs. Value of Power System Benefits

Phase 2 type studies are typically performed by the Transmission owner or its consultant. The main study tools and FACTS model requirements for Phase 2 type studies are:

- Load Flow Programs
- Stability Programs
- Positive Sequence Modeling Only
- Full Scale Model of the Power System
- Device Models
- Load flow models
- Stability models
- Control models

The basic modeling and study requirements for Phase 2 type studies are similar to Phase 1 type studies, with the added requirement of more detailed device models. Electromagnetic transients analysis is typically not required at this stage, typically undertaken by the utility/transmission owners, all the way through to the

system studies and modeling issues associated with the every-day operation of an installed FACTS controller in a specific power system. The following subsections provide the basic objectives and selected details for each study phase in a bullet list format of the presentation material.

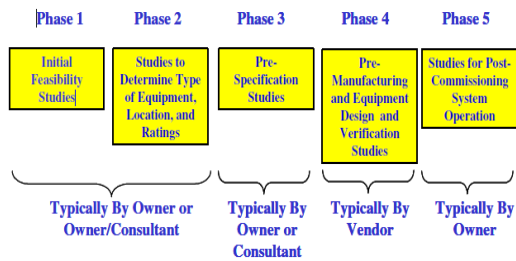


Figure 4. Phases of power system studies for FACTS installation projects

A. Phase 1: Initial Feasibility Studies to Determine System Constraints and Reinforcement Needs

The key objectives for Phase 1 type studies to be discussed in the presentation that will accompany this paper are:

- Identify Characteristics of the Power System
- Identify System Performance Problems
- Transient instability
- Oscillatory instability
- Dynamic voltage instability
- Voltage collapse
- Thermal ratings (power flow)
- Identify which Transmission Constraints that can be

Examined Independently and which Require a Coordinated Analysis

- Identify the Reinforcement Needs (Shunt vs. Series and Fast vs. Slow)

Phase 1 type studies are typically performed by the transmission owner or its consultant. The main study tools and FACTS model requirements for Phase 1 type studies are:

- Load Flow Programs
- Stability Programs
- Positive Sequence Modeling Only
- Full Scale Model of the Power System
- Simple Device Models are Adequate for Study Phase 1

The end results (deliverables) of Phase 1 type studies are:

- A Fundamental Understanding of the Characteristics of the Power System
- Key areas and interfaces affected
- Identification of the System Performance Problems
- Transient instability
- Oscillatory instability
- Dynamic voltage instability
- Voltage collapse
- Thermal ratings (power flow)
- Identification of which Constraints can be Examined

Independently and which Require Coordination

- Identification of the Most Effective “Type” of System

Reinforcements (Shunt vs. Series and Fast vs. Slow)

B. Phase 2: Studies to Determine Type of Equipment, Location, and Ratings

The key objectives for Phase 2 type studies to be discussed in the presentation that will accompany this paper are:

- Identify Solution Options, both Conventional and FACTS and Combinations Thereof
- Evaluate Performance of Solution Options Consider Other Issues
- Location
- Economics of the solution options

If the analysis of Phase 1 indicates that the system has a problem with voltage, then in Phase 2 it is necessary to identify solution options for system voltage control. include:

For Dynamic (fast) Voltage Instability, Consider:

- Shunt capacitor banks
- Static shunt compensators (e.g., STATCOM, SVC)
- Combination

For Voltage Collapse (slow), Consider:

- Shunt capacitor banks
- Series capacitors
- Static shunt compensators (e.g., STATCOM, SVC)
- Static series compensators (e.g., SSSC)
- Combination

If the analysis of Phase 1 indicates that the system has a problem with rotor angle stability, then in Phase 2 it is necessary to identify solution options for this type of problem. These include:

For Transient Instability, Consider:

- Series capacitors
- Static shunt compensators (e.g., STATCOM, SVC)
- Static series compensators (e.g., SSSC)
- Combination

For Oscillatory Instability, Consider:

- Power system stabilizers (PSS)
 - Damping controls added to static shunt or series compensators
- The end results (deliverables) of Phase 2 type studies are:

- Identification of Viable Solution Options
- Consider both conventional and FACTS and combinations thereof
- Rank all viable solutions in terms of system benefits
- Identification of Suitable Location to Install the Solution Options
- Choice may be obvious or depend on the solution to be implemented
- Site work and permitting etc. may be a key factor
- Evaluation of Economics of Each Option’s Overall Costs vs. Value of Power System Benefits
- Rank all viable solutions in terms of overall economics

C. Phase 3: Pre-Specification Studies for Defining Equipment Requirements

The key objectives for Phase 3 type studies to be discussed in the presentation that will accompany this paper is:

To be Able to Write a Technical Specification and RFP to Submit to Potential Bidders

Phase 3 type studies are typically performed by the transmission owner or its consultant. There are a variety of technical items to be published in a technical specification that must be determined a priori by system studies. These include, but are not limited to, the following:

- Device Type, Rating, and Location (From Phase 2 Studies)

System Descriptions

-Minimum and maximum operating voltage for steady state and transient conditions (MCOV, BSL, BIL, etc)

-Minimum, maximum, emergency, and ultimate system strength and corresponding X/R ratios

-Minimum and maximum frequency excursions

-Maximum unbalance (negative and zero sequence)

- System Dynamic Performance Requirements

-To develop strategies for system steady-state and transient performance

- Harmonic Limits and System Characteristics

-Maximum individual harmonic distortion (Dn)

-Maximum total harmonic distortion (D)

-Telephone interference limit (TIF)

-Impedance envelopes for normal and contingency conditions

- High-frequency Interference Issues and Limits

-To determine maximum acceptable limits on power line carrier (PLC) noise and radio interference (RI) noise

- Other Items to Prepare

-System one-line diagram and impedance map

-Load flow and stability data sets

-Equipment performance requirements

--Control objectives (steady state and transient)

--Response times

--Voltage imbalance

--Availability/Reliability criteria

--Acceptable Failure Rate of components

-Loss evaluation criteria, formula, and associated cost/penalty

List of required system studies by vendor (See Phase 4 type studies) There are numerous other items that belong in the Technical Specification, but are not directly related to system study issues. These items will be mentioned in the presentation that will accompany this paper, but not discussed

in detail. The end result (deliverable) of Phase 3 type studies is: A Technical Specification and RFP to Submit to Potential Bidders

D. Phase 4: Pre-Manufacturing and Equipment Design and Verification Studies

The key objectives for Phase 4 type studies to be discussed in the presentation that will accompany this paper are:

- To Verify to the Owner that the Device Described by the

Specification meets all System and Equipment Performance Requirements

E. Phase 5: Studies for Post-Commissioning System Operation

The key objectives and deliverables for Phase 5 type studies to be discussed in the presentation that will

accompany this paper are:

- To Confirm the Network Load Flow Conditions are Within Benchmark Limits
- To Confirm Installed Equipment is Effective to Enhance Network Steady-state and Dynamic Performance
- To Setup Instrumentation and Obtain Measurements During Staged Fault Tests and Actual Faults/Dynamic Events
- To Ensure There are no Adverse Interactions with Other System Equipment
- To Measure Reliability/Availability of Equipment To Establish Operational Losses Algorithm

Phase 5 type studies are typically performed by the transmission owner.

IV. OVERVIEW OF FACTS CONTROLLER CIRCUITS

This section provides a sample of some of the FACTS controller circuits and system performance characteristics that will be discussed during the presentation that accompanies this paper. The focus of the presentation will not be on the detail circuit topologies, but rather on the limitations and controllability of ac systems using the FACTS controllers along with its basic attributes and configurations.

A. Static Var Compensator

Figure 5 shows the basic circuit for a Static Var Compensator (SVC). Figure 6 shows its voltage-current characteristics. These will be discussed in detail in the presentation that will accompany this paper.

B. Static Synchronous Compensator

Figure 7 shows the basic circuit for a Static Synchronous Compensator (STATCOM). Figure 8 shows its voltage current characteristics. These will be discussed in detail in the presentation that will accompany this paper.

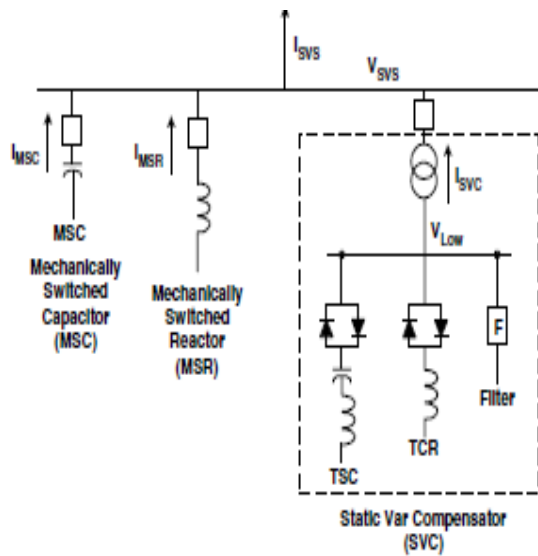


Figure 5. Circuit for a Static Var Compensator (SVC)

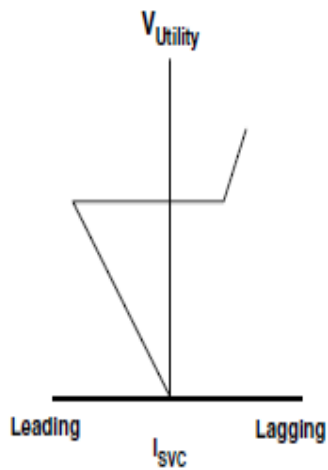


Figure 6. V-I characteristics of a SVC

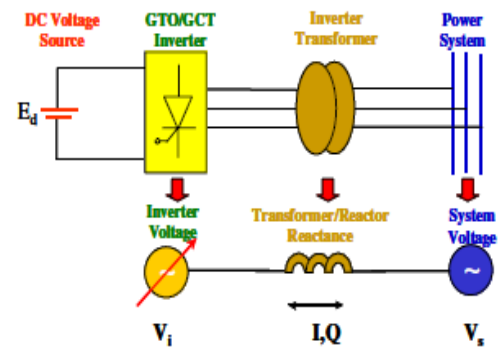


Figure 7. Circuit for a Static Synchronous Compensator (STATCOM)

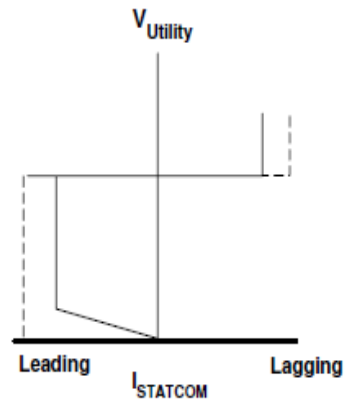


Figure 8. V-I characteristics of a STATCOM

C. Unified Power Flow Controller

Figure 9 shows the basic circuit for a Unified Power Flow Controller (UPFC) and Figure 10 shows a Static Synchronous Series Compensator (SSSC). Figure 11 shows the phasor diagrams depicting the UPFC operation and its impact on the power system, and Figure 12 illustrates the control modes of the series compensator (UPFC or SSSC) (the characteristics of the shunt portion of the UPFC is similar to Figure 8). These, along with the VTM-X phasor characteristics will be discussed in details in the presentation that will accompany This paper.

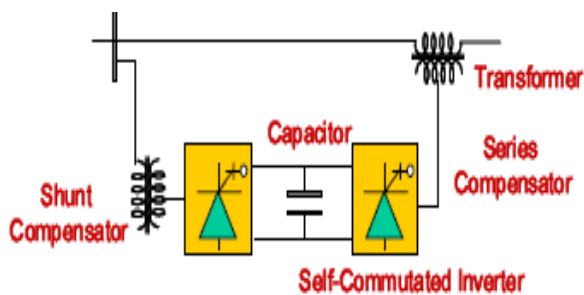


Figure 9. Circuit for a Unified Power Flow Controller (UPFC)

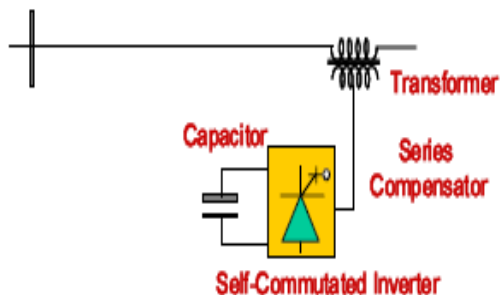
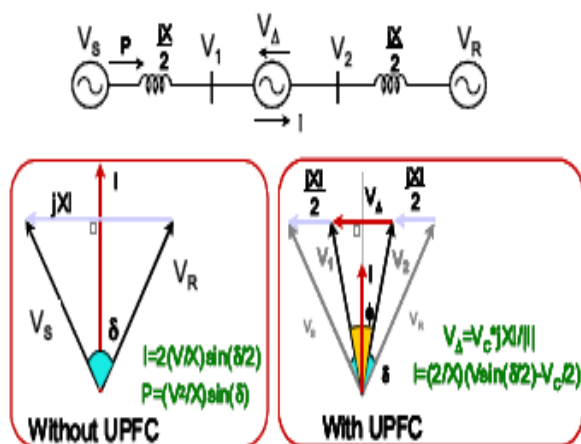


Figure 10. Circuit for a Static Synchronous Series Compensator (SSSC)



D. Thyristor Controlled Series Compensator

Figure 13 shows the basic circuit for a Thyristor Controlled Series Compensator (TCSC). Figure 14 shows its impedancecurrent (X-I) characteristics for both a single-module and multi-module controllers. These will be discussed in detail in the presentation that will accompany this paper.

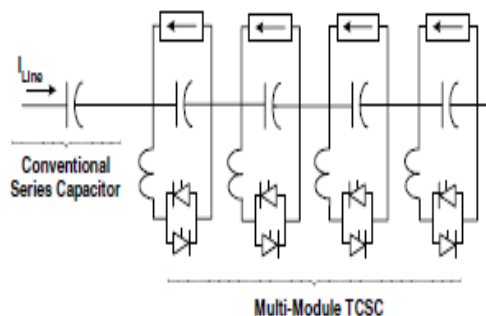


Figure 13. Circuit for a Thyristor Controlled Series Compensator (TCSC) [19]

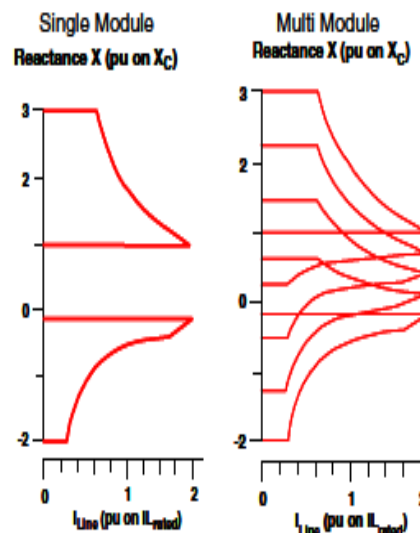


Figure 14. X-I characteristics of a TCSC [19]

V. SUMMARY

This paper was on Part I of the session and focused on a summary of the issues and benefits of applying FACTS controllers to AC power systems. The overall process for system studies and analysis associated with FACTS installation projects and the need for FACTS controller models was also discussed. Finally, an introduction to the basic circuits of several FACTS controllers was provided with a focus on their system performance characteristics. This paper was designed to be accompanied by the presentation material.

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